A GRAPHICALLY INTERACTIVE APPROACH TO STRUCTURED AND UNSTRUCTURED SURFACE GRID QUALITY ANALYSIS

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Abstract

A graphically interactive approach to structured and unstructured surface grid quality analysis is described. A Surface Analysis Code (SurfACe) is developed to help a user analyze surface grid quality based on surface normal vectors, first and second derivatives of these vectors, normal, Gaussian, and mean curvatures, orthogonality, aspect ratio, and cell area. The results demonstrate how this approach can be used to reduce surface grid generation errors and increase the cost effectiveness of Computational Fluid Dynamics as an aircraft design tool.

Introduction

Computational Fluid Dynamics (CFD) has progressed rapidly in the last few years. It is now possible to generate viscous volume grids and obtain full Navier−Stokes solutions about complex aerodynamic configuration in a matter of days. Comparable wind tunnel tests often require months to complete. The cost effectiveness of CFD analysis has resulted in its wide use as an aircraft design tool. Preliminary aircraft designs are now created and evaluated before the first prototype wind tunnel model is produced.

CFD analysis is typically preceded by the creation of a computational volume grid. This grid is generally of two types — structured or unstructured (or in some cases a combination of the two). A structured grid has an inherent numbering system in which the neighbors of each grid point are known explicitly. An unstructured grid, on the other hand, does not have an explicit numbering system. The neighboring grid points of any particular point are only known through the use of a connectivity table.

The first step in generating either type of CFD volume grid is to generate a surface grid on the solid surface of the vehicle. This is done by putting grid points on some type of pre−defined surface representation. Many aircraft and spacecraft are now being designed using Computer−Aided Design (CAD) packages. These packages represent the solid surfaces of a vehicle using Non−Uniform Rational B−Splines (NURBS), B−spline, ruled, or other representation [1,2]. A surface grid is then created on these surface models.

A number of software packages exist for

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creating surface grids [3,4,5], but few of these display more than a wireframe or shaded display of the grid. These types of displays will not indicate subtle changes in surface grid curvature, orthogonality, cell area, or other parameters important in CFD analysis of aircraft. These anomalies, however, can result in pressure distributions and flowfield characteristics which are not consistent with the true flowfield characteristics of the vehicle. If this occurs, a great deal of work must be repeated in order to alleviate these errors. This is a costly and time consuming procedure.

SurfACe reduces or eliminates many surface grid generation errors by efficiently evaluating surface (computationally two−dimensional) grids. It is a graphically interactive surface grid analysis program which evaluates both structured and unstructured surface grids based on a number of grid quality parameters.

Surface Grid Analysis

Surface grids can be analyzed using a number of different parameters. The most useful parameters fall into two classes — those that calculate changes in surface curvature and those that calculate changes in surface grid quality. The first class of parameters include the magnitudes of the x−, y−, and z−components of the surface normal vectors, first and second derivatives of these vectors, and the normal, Gaussian, and mean curvatures. These parameters are used to determine whether a surface grid contains the desired degree of smoothness. Any ‘‘bumps’’ or ‘‘valleys’’ in the surface grid will be highlighted by one or all of these curvature parameters. It is up to the user to determine whether these curvature properties are a desired part of the model or were introduced when the surface grid was created on the mathematical model of the surface.

The second class of parameters include surface grid cell area, orthogonality, and aspect ratio. These parameters are used to determine if a surface grid has enough refinement to result in a high quality volume grid and accurate flowfield solution. The type of flow solver used must be kept in mind when evaluating a surface grid using these parameters. Surface grid cell area, for instance, must be much smaller near the leading edge of a wing when using a full Navier−Stokes solver than when using an Euler solver.

SurfACe calculates all of the above parameters and allows for additional parameters to be added through the use of a function input file. Each parameter is displayed using a variable color map. Wireframe, hidden line, and shaded views of the surface grid are also available. The calculations of the pre−defined parameters for structured and unstructured surface grids are given below. Parameters are calculated as cell−centered values as well as point−centered values. This allows for accurate analysis of the surface grid regardless of whether a flat or gauroud display (both are available in SurfACe) of the surface grid is used.

Structured Surface Grid Parameters

The following calculations are used to determine the structured surface grid analysis parameters.

Surface Normal Vector

The surface unit normal vector for each grid point is calculated from,

$$\bar{n} = (\bar{r}_\xi \times \bar{r}_\eta) / \| \bar{r}_\xi \times \bar{r}_\eta \| , \qquad (1)$$

where $\bar{r}_\xi$ and $\bar{r}_\eta$ are the surface grid tangential vectors in each computational coordinate direction. The normal for each grid cell is also calculated using Eq. 1 where $\bar{r}_\xi$ and $\bar{r}_\eta$ are the diagonal surface grid tangential vectors for each grid cell. All surface normal vectors are unit vectors and are therefore not affected by surface grid cell area.

SurfACe plots the magnitude of the x−, y−, and z−components of the surface unit normal vector using a variable color map. Each component is plotted separately in order to highlight changes in the scalar magnitudes of these values throughout the entire surface grid. A shaded view of the same grid may not show these changes since all three components of the surface normal vector are used in plotting the shaded representation. An abrupt change in the magnitude of the x−component of the surface normal vector may be masked by larger magnitude y− and z−components of the vector.

First Derivative of Surface Normal Vector

The first derivative of the surface normal vector for each grid point is calculated using the absolute value of the centered difference between the center grid point and the eight surrounding grid points. The cell centered first derivative is calculated in a similar manner except that the cell centered normals are used in the calculation.

SurfACe displays the scalar magnitude of the derivative using a variable color map which is initially scaled from zero to one. Rapidly changing colors on the surface grid indicate areas where the slope of the surface is changing. Only large changes in the slope of a surface grid would be visible using a shaded representation of the surface grid.

Second Derivative of Surface Normal Vector

The second derivative of the surface normal vector for each grid point and grid cell is calculated and displayed in much the same way as the first derivative. Only the centered difference approximation changes. Changes in the second derivative of the surface normal vectors for a surface cannot be detected from a shaded image of a surface grid. SurfACe, however, will clearly display these changes with a sharp change in color.

Curvature

Normal, Gaussian, and mean curvature are calculated as given in Ref. 6. These are the classical definitions of curvature which are standards in the Computer−Aided Geometrical Design (CAGD) field. These values are particularly useful in comparing Computer−Aided Design (CAD) definitions to surface grids generated on these definitions.

Orthogonality

Surface grid orthogonality is calculated for each grid point by first calculating the angles formed by the intersection of the surface grid lines in each computational coordinate direction. Orthogonality is then assigned the value of the sum of the absolute value of the deviation of each angle from the average of the four angles. Grid cell orthogonality is calculated in a similar manner except that the four angles used are the interior angles of the grid cell rather than the four angles surrounding a grid point.

Plots of orthogonality using SurfACe show brightly colored regions in areas where there exists a high degree of surface grid skewness (i.e. lack of orthogonality). It is difficult to judge the skewness of a surface grid by simply examing the grid itself. The grid may appear to be skewed depending on the rotational orientation of the vehicle. SurfACe, however, highlights orthogonality independent of the orientation of the vehicle.

Area

Surface grid area is calculated for each grid point as one−quarter of the area formed by the four surrounding grid cells. The area assigned to each grid cell is calculated directly. Surface grid cell area is an important quantity in structured grids. Abrupt changes in cell area may cause erroneous flowfield solutions. These changes are not always easy to detect by looking only at a wireframe display of a grid. Surface grid cells with high aspect ratios may appear to have the same cell area as their neighbors while in reality the cell area may be quite different. SurfACe will highlight these regions with a bright change in color such that they will be easily detectable.

Aspect Ratio

The aspect ratio for each grid point is calculated as simply the area of the four surrounding grid cells divided by the square of the perimeter of these cells. A coefficient scales the resultant such that the aspect ratio is always between zero and one. The aspect ratio assigned to each grid cell is calculated for the individual cell rather than from the four surrounding cells.

Surface grid cells with high aspect ratios are highlighted with bright colors in SurfACe. These cells can often be detected by looking directly at the wireframe display of the surface grid. Abrupt changes in aspect ratio, however, are more difficult to detect from the wireframe display. These regions are seen in SurfACe by rapidly changing colors on the surface grid.

Unstructured Surface Grid Parameters

The unstructured surface grid parameters are calculated in much the same way as the structured surface grid parameters. There is, however, one fundamental difference. The number of neighboring surface grid points for a structured grid is always known. The number of neighboring points for an unstructured grid is completely arbitrary. Parameters assigned to grid points must be calculated using the information from all of the surrounding grid points. Therefore the orthogonality, area, and aspect ratio of each grid point is an average of all of the immediate neighbors to that grid point. Parameters assigned to grid cells are simply calculated for the individual cell and no averaging is required.

First and second derivatives of the surface grid normal vectors are treated in much the same way. A one−sided differencing between the central grid point and each of the surrounding grid points is first calculated and the result is divided by the number of connected grid points. The classical definitions of curvature are not applicable to unstructured grids and are therefore not calculated.

SurfACe Interface

The user interface for SurfACe is shown in Fig. 1. SurfACe runs in a multi−window environment on a Silicon Graphics Iris 4D workstation. As shown in Fig. 1, there are six windows. Three control the way in which the data is displayed, two are for help and the last is the viewing window which displays the surface grids. The rotation, translation, and scaling (zooming) of the surface grid are controlled using the keyboard and mouse (as in Ref. 3). There are also a number of other viewing options controlled by the keyboard. All of these are explained using the ‘‘Help With...’’ window in the lower right−hand side of the SurfACe interface. The operation of each menu item is also displayed continuously in the ‘‘Help Text Window.’’ In this way, a new user can learn to use SurfACe with little or no formal instruction.

SurfACe accepts binary and formatted PLOT3D, GRIDGEN, Lawgs and unstructured FAST surface grid file formats. These files are presently input into SurfACe using command line flags.

Display

SurfACe displays a surface grid as a wireframe, shaded, hidden line, or analyzed representation. ‘‘Analyzed’’ simply means that colored polygons are drawn on the surface grid. The polygons are colored using a color map which can be adjusted by the user. Flat (each grid cell is a single color) or gouraud (each grid point is a single color) shaded and analyzed displays are available. Each display is important because curvature parameters are typically defined at grid points and are therefore more accurately displayed using a gauroud display. Grid quality parameters are typically defined at grid cell centers and are therefore more accurately displayed using a flat display.

Hidden line plotting is accomplished by drawing a black polygon behind the wireframe. The offset distance between the polygon and the wireframe is varied continuously with the scaling. In this way, the grid will not become covered by the polygons when the vehicle is small in scale nor will a user be able to see the offset distance when the vehicle is large in scale.

Results

Figure 2 shows the shaded representation of a space shuttle surface grid. Wireframe and shaded representation of a surface grid are typically the only ones available in most grid generation packages. The surface grid in this figure appears to be perfectly smooth. If the surface grid is highlighted based on the magnitude of the x−component of the surface normal vectors, however, a user can immediately identify regions of the surface grid which are not smooth (Fig. 3). These regions, below the windshield and on the bottom of the vehicle near the symmetry plane, are clearly visible as rapid and somewhat random changes in color. If a volume grid was generated and flow solutions were obtained using this surface grid, erroneous flow solutions would result. By detecting these problems early in the grid generation process, a great deal of time and money can be saved.

Figure 4 shows a structured surface grid for the Mach 3.0 High Speed Civil Transport (HSCT) [7] configuration with engine nacelles. Analysis of the surface grid based on grid cell area shows a discontinuity in surface grid cell area approximately halfway down the length of the vehicle. This discontinuity in area is not easily detected from a hidden line plot (Fig. 4).

Figure 5 shows a shaded and hidden line representation of an unstructured surface grid for the Mach 3.0 HSCT configuration. This grid was generated by extracting a number of grid lines (the black lines drawn on the shaded representation) from a structured grid and using an advancing front [8] technique to generate the interior unstructured grid points. This technique makes no attempt at placing the resulting grid points on a smooth representation of the surface. Figure 5 shows what appears to be an adequate surface grid for this vehicle.

An analysis of the resulting unstructured grid based on the magnitude of the x−component of the surface normal vectors shows abrupt changes in color towards the rear of the aircraft (top half of Fig. 6). These color changes indicate that the slope is not continuous across the advancing front boundaries. An analysis of the structured surface grid from which the advancing front boundaries were taken is given in the bottom half of Fig. 6 for comparison. No abrupt changes are seen on the structured grid indicating that the unstructured grid is not of sufficient quality and must be regenerated.

Conclusions

In order for CFD analysis to be used to its fullest potential as an aircraft and spacecraft design tool, surface grid quality errors must be eliminated. These errors are difficult to detect from wireframe and shaded representations of a surface grid. This is especially true for complex aerodynamic configurations. If, however, the methods described here are applied to these configurations, most grid quality errors can be easily detected early in the grid generation process. This saves countless hours spent in repeated work and ultimately increases the cost effectiveness of CFD as an aircraft design and analysis tool.

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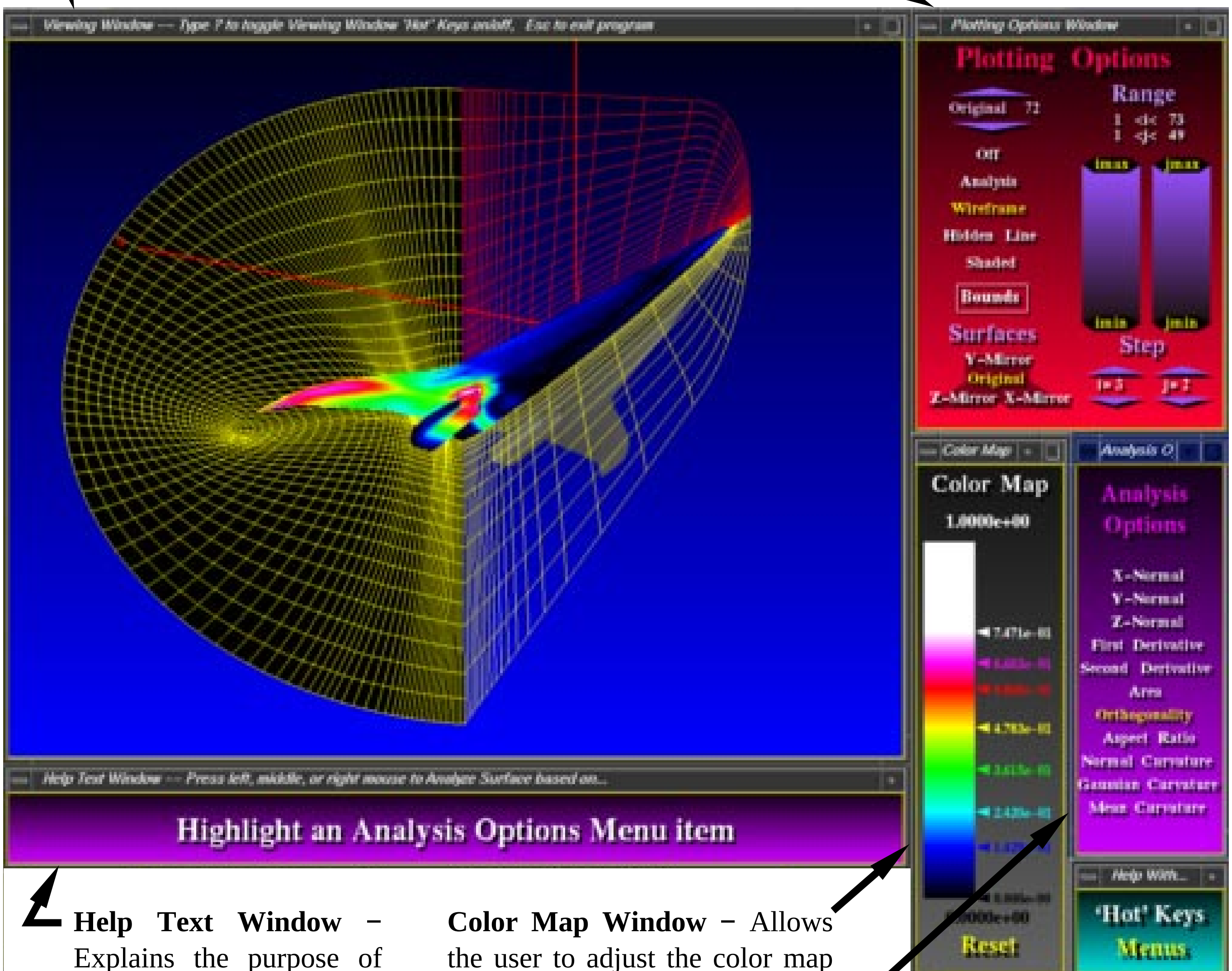
Viewing Window − Allows the user to rotate, translate, or scale the wireframe, hidden line, shaded or analyzed representation of the surface grid.

Plotting Options Window − Allows the user to specify the way in which the data is displayed.



Help Text Window − Explains the purpose of any SurfACe menu item highlighted by the cursor.

Color Map Window − Allows the user to adjust the color map in order to highlight a particular region of the surface grid.

Help With... Window − Turns help on and off.

Analysis Options Window − User specifies which parameter to use when analyzing a surface grid.

Fig. 1 SurfACe interface

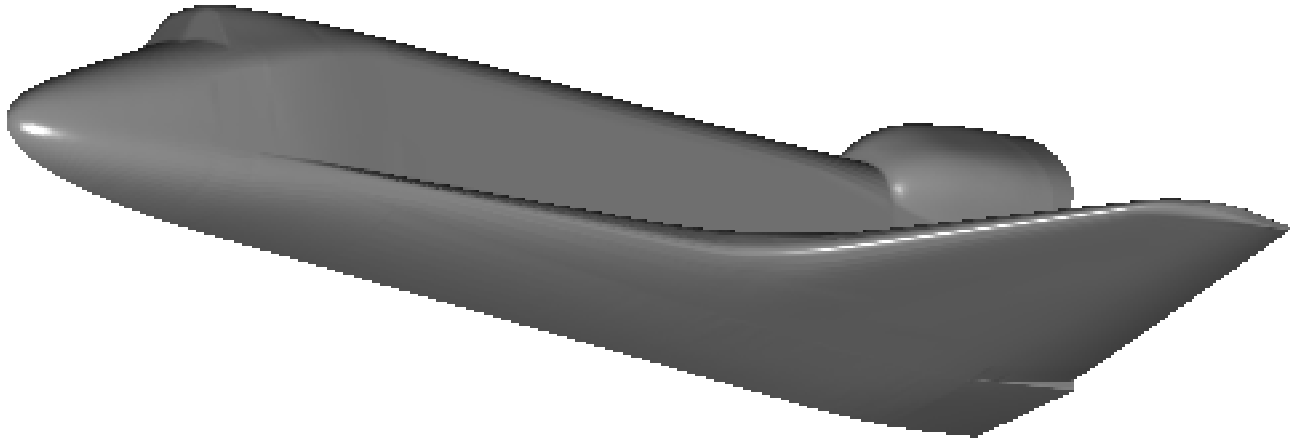


Fig. 2 Shaded display of space shuttle surface grid

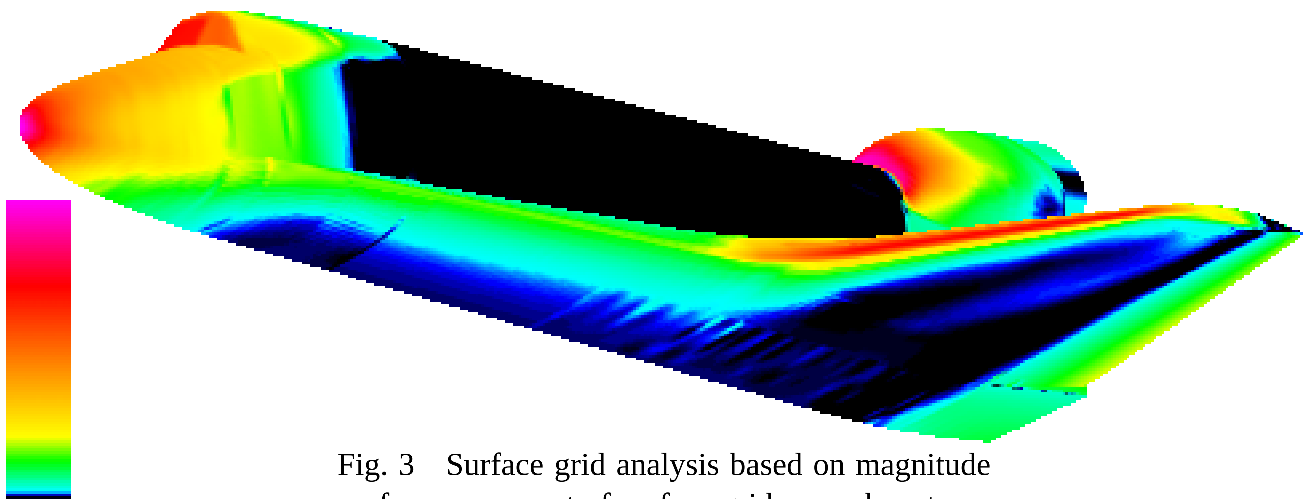


Fig. 3 Surface grid analysis based on magnitude of x−component of surface grid normal vectors

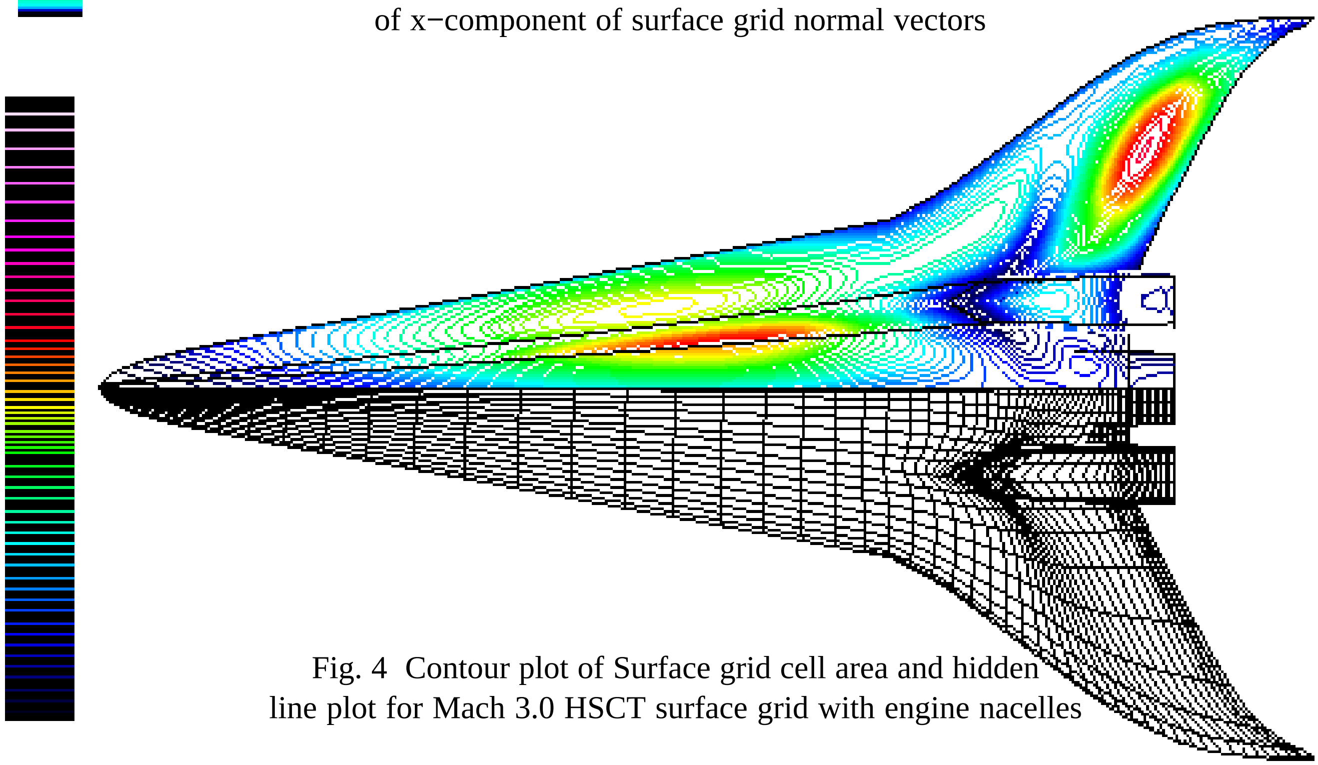


Fig. 4 Contour plot of Surface grid cell area and hidden line plot for Mach 3.0 HSCT surface grid with engine nacelles

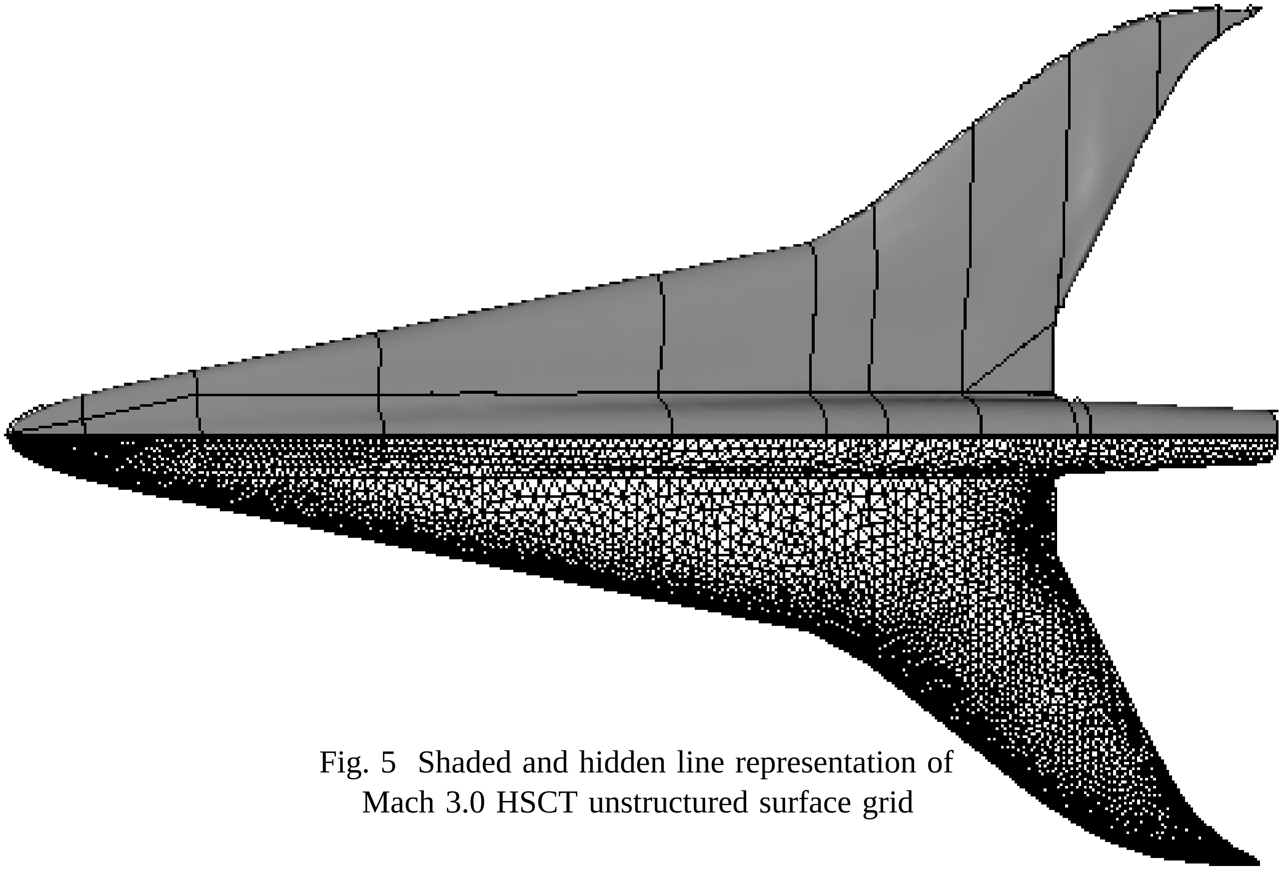


Fig. 5 Shaded and hidden line representation of Mach 3.0 HSCT unstructured surface grid

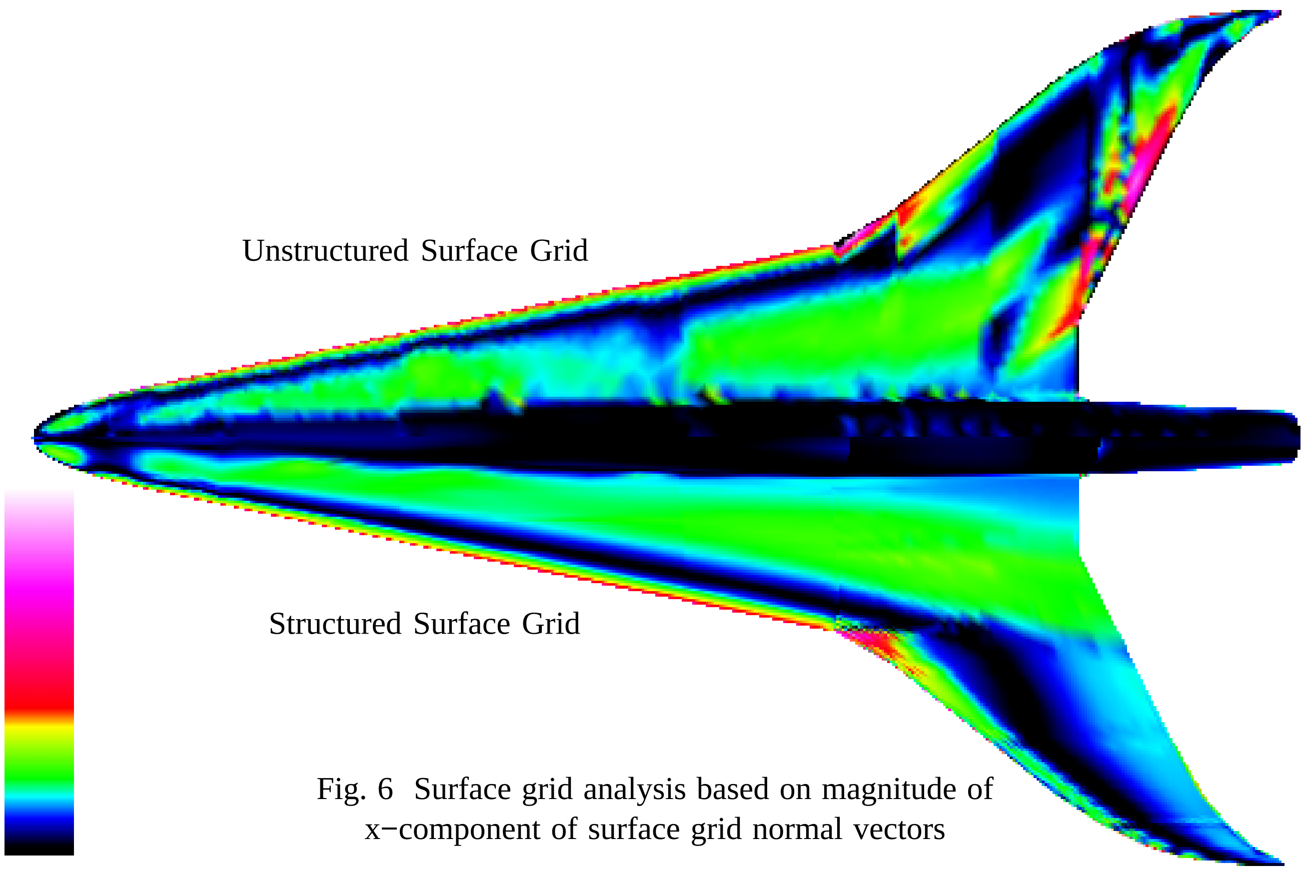


Fig. 6 Surface grid analysis based on magnitude of x−component of surface grid normal vectors